
Beam Simulation and Event Rates for a Wide-Band Low-Energy Neutrino Beam

From the FNAL MI to a DUSEL site

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Introduction

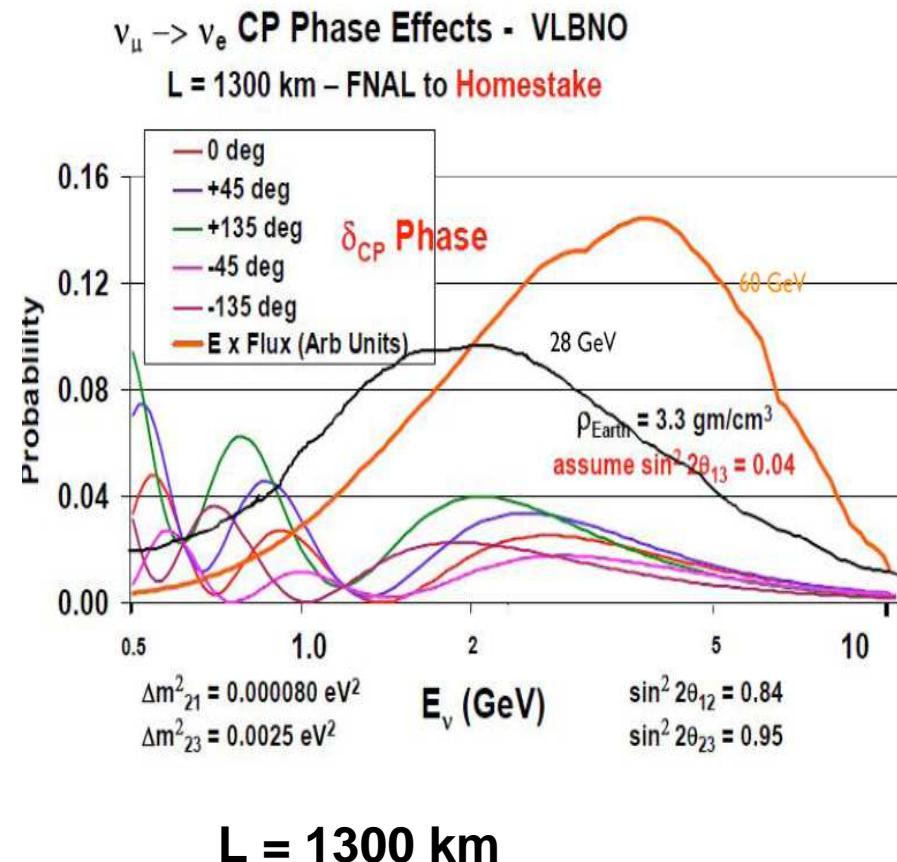
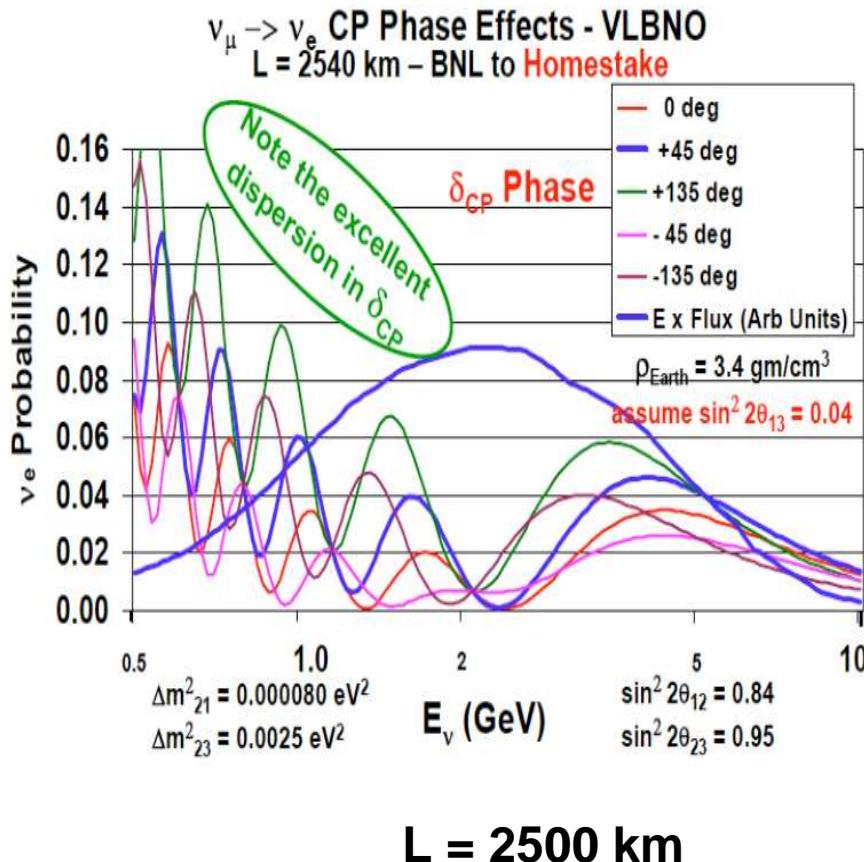
It has previously been demonstrated that an on-axis wide-band neutrino beam directed at $\mathcal{O}(100)$ kilo-ton scale neutrino detector located at a baseline greater than 1000 km is a powerful precision probe of the parameters of the neutrino mixing matrix, the mass hierarchy and CP-violation. hep-ex/0407047.

The Main Injector (MI) 120 GeV proton accelerator at Fermi National Accelerator Laboratory (Fermilab) is a possible source of a high-intensity neutrino beam for VLBNO experiments; with $\geq 1000\text{km}$ baselines to either one of the currently proposed DUSEL sites (Henderson, Homestake).

We present a simulation of a wide-band low-energy (WBLE) on-axis beam using the Fermilab MI and compute the ν fluxes and event rates at a detector located 1300 km from FNAL.

Beam Design Requirements

The design specifications of a new WBLE beam based at the Fermilab MI are driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations.

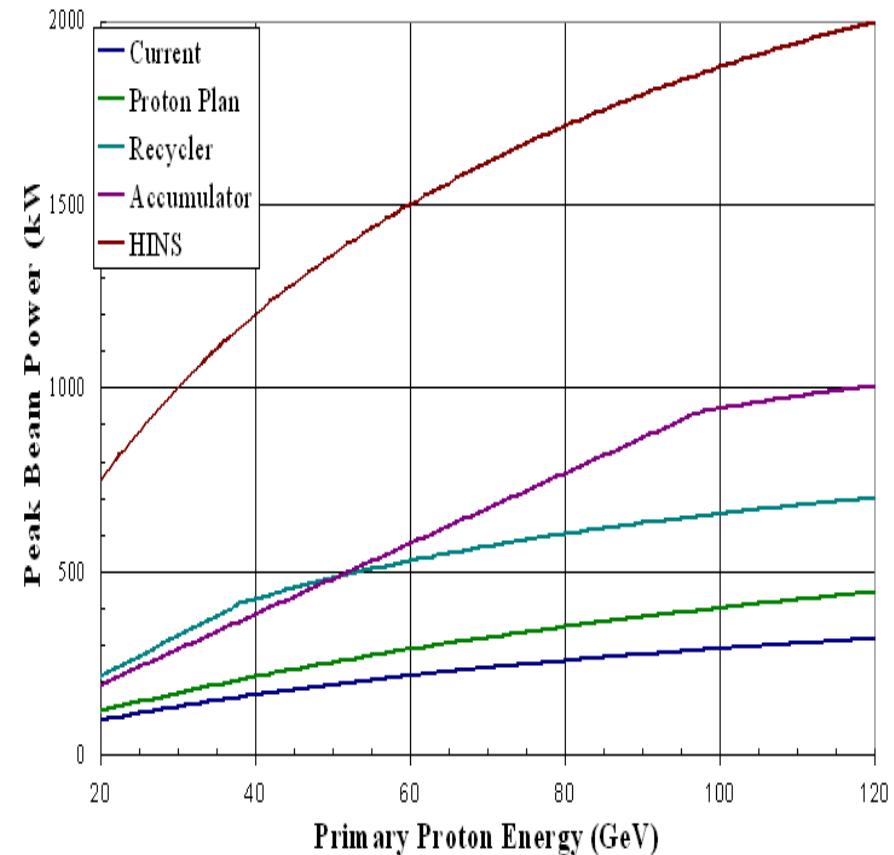
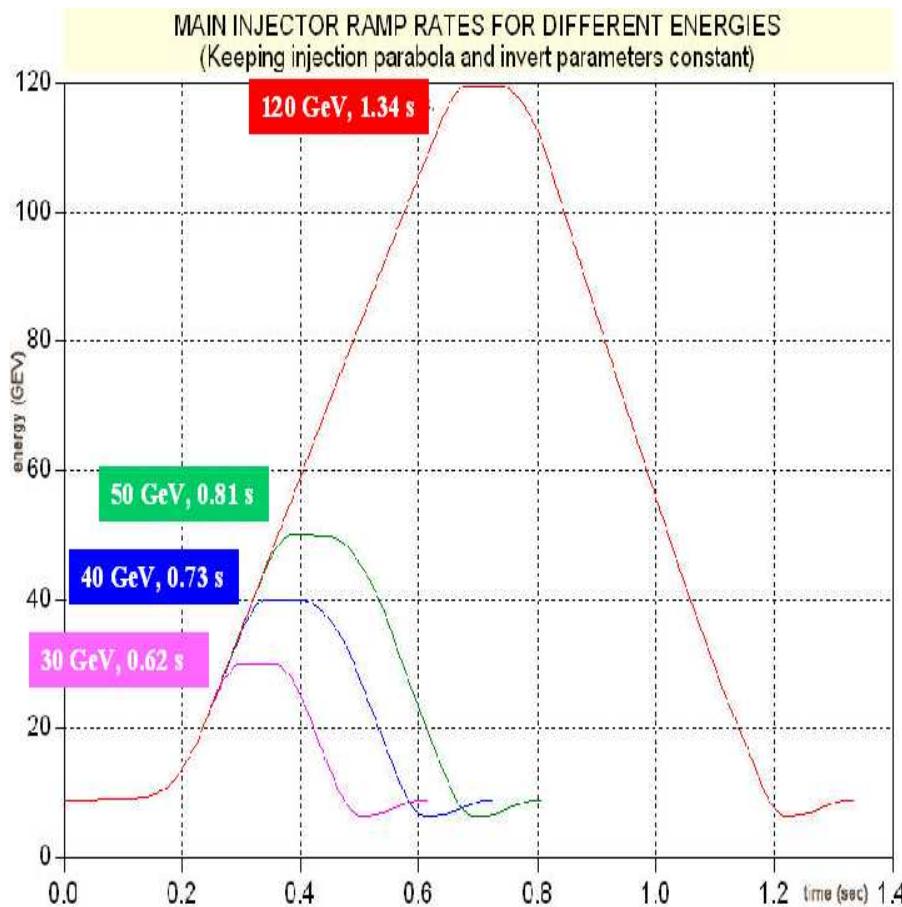


Beam Specifications $L = 1300$ km

1. We require the maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, the maxima of which occur at 2.4 and 0.8 GeV respectively.
 2. Since neutrino cross-sections scale with energy, larger fluxes at lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node and beyond.
 3. To detect $\nu_\mu \rightarrow \nu_e$ events at the far detector, it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.
 4. The irreducible background to $\nu_\mu \rightarrow \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with negligible ν_e contamination is required.
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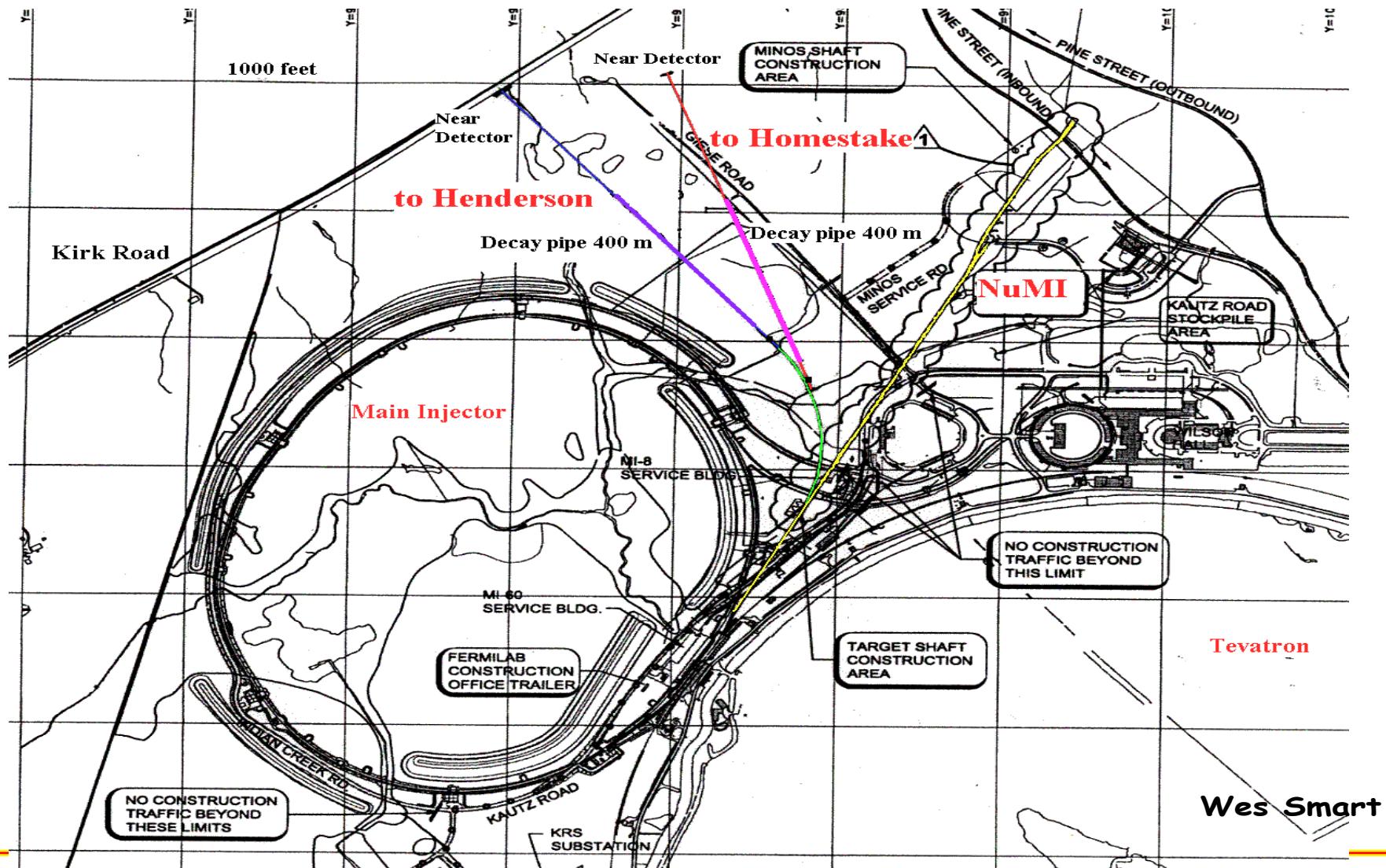
Beam Specifications: E & Power

See Bob Zwaska's (FNAL) talk next....



Beamline Siting

Greg Bock, Dixon Bogert, Wes Smart (FNAL)



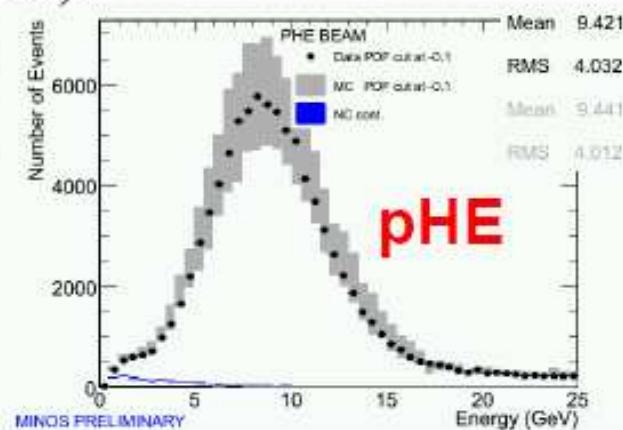
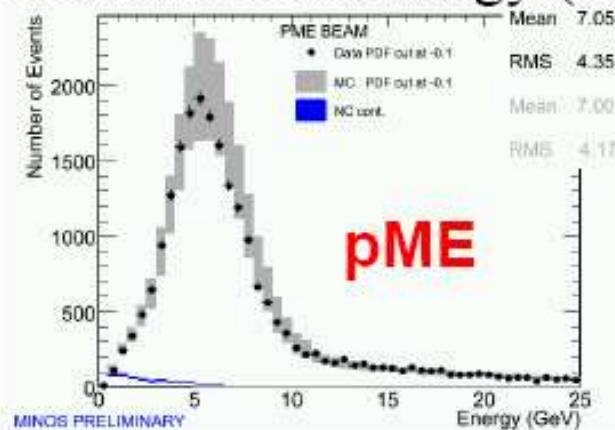
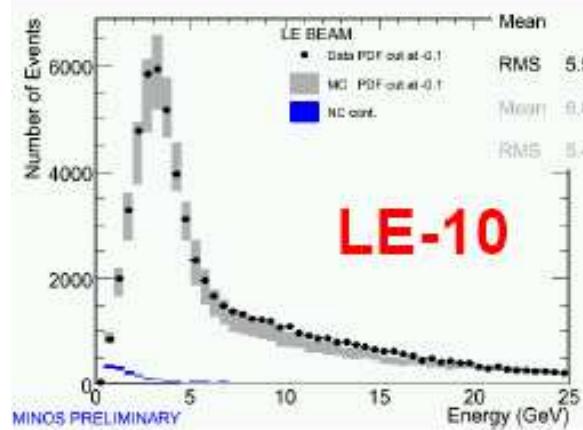
Beamline Simulation

- We have adopted GNUMI v18, the GEANT 3.21 simulation framework developed for the NuMI beamline, for this study.
- We have implemented the target and horn design developed for the AGS very long baseline neutrino program (BNL-73210-2004-IR at <http://nwg.phy.bnl.gov>). The target and horn designs implemented have been optimized for a 28 GeV 1-2 MW proton beam.
- Simulation of hadro-production of the proton beam on the target is performed using Fluka 2005.
- The particles produced from the target are transported through the beamline using GEANT. GEANT-FLUKA is used for modeling secondary interactions between hadrons produced from the target and beamline components.

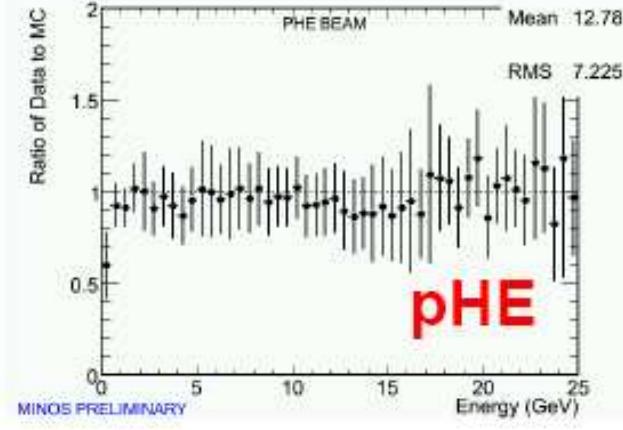
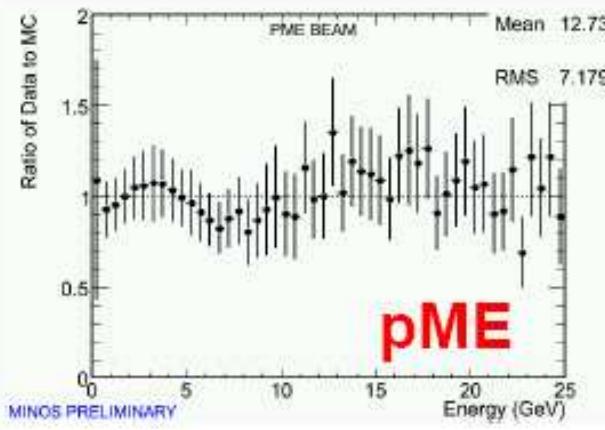
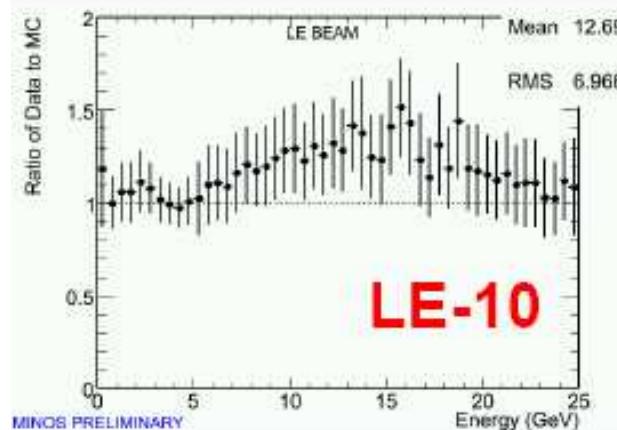
How well does it work?

NuMI Data/MC normalized to the number of POT:

Reconstructed Energy (GeV)

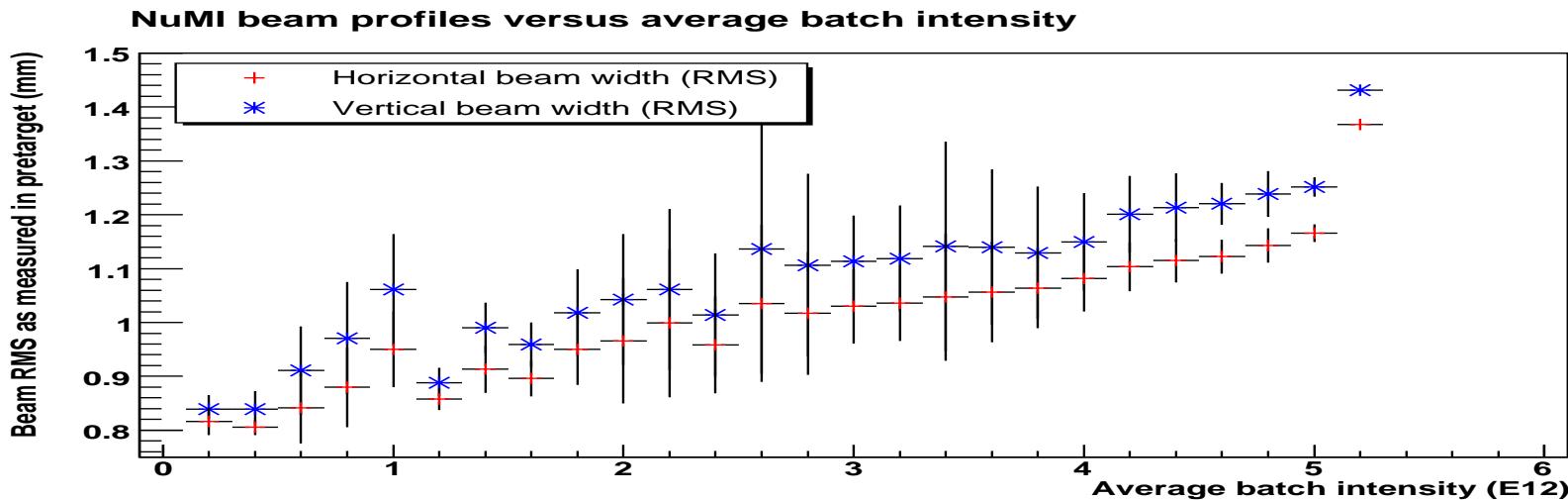


Ratios of Data/MC



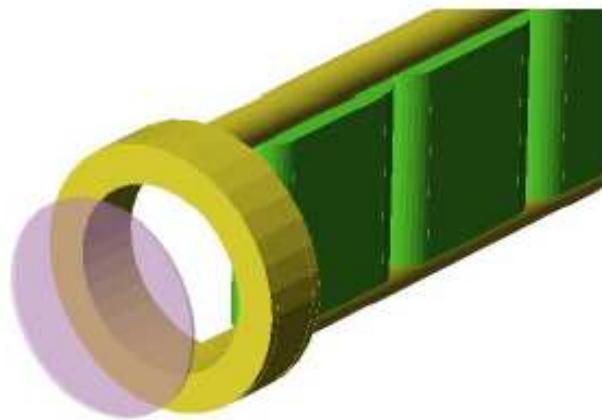
NuMI/WBLE differences

| Component | NuMI | WBLE |
|------------------|--|---|
| Target: | rectangle, 6.4mmx20mmx1m graphite | tube, $r=6\text{mm}$, $l=0.6\text{m}$ graphite |
| Horns: | 2 2 paraboloids/horn Al | 2 multi cylinders/horn Al |
| Target shielding | upstream baffle, budal monitor cement blocks | no baffle, no budal monitor no blocks |
| Beam: | $\sigma_x = 1.1\text{mm}$, $\sigma_y = 1.25\text{mm}$ | $\sigma_x = 1.5\text{mm}$, $\sigma_y = 1.5\text{mm}$ |



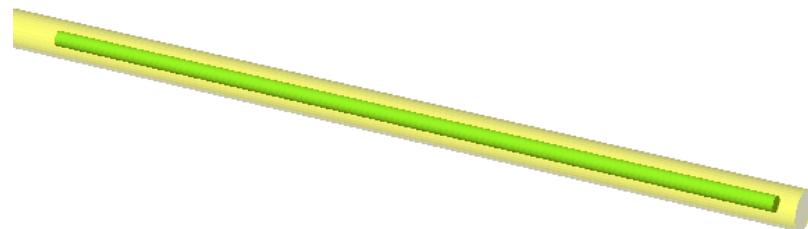
Target simulation with Fluka 05

NuMI Fluka 05 target geometry



Target water cooling pipes, canister window, biscal monitor, and Al can are in the simulation.

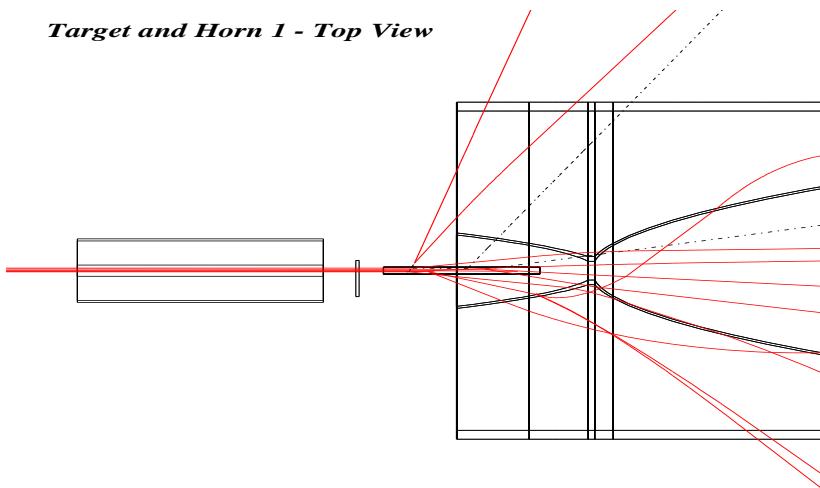
WBLE Fluka 05 target geometry



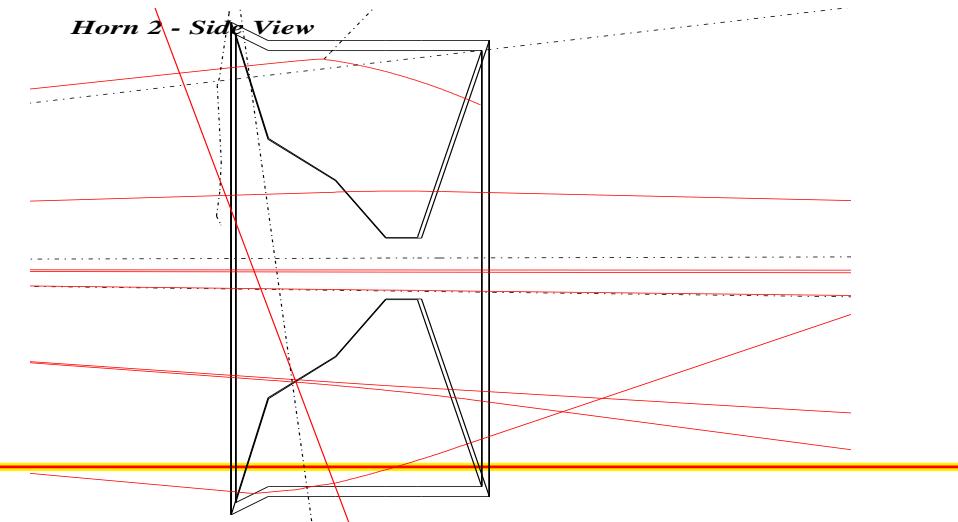
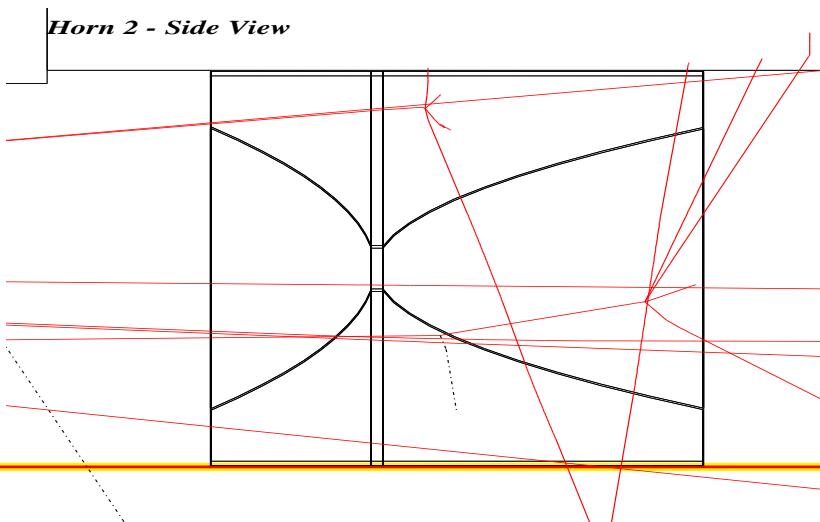
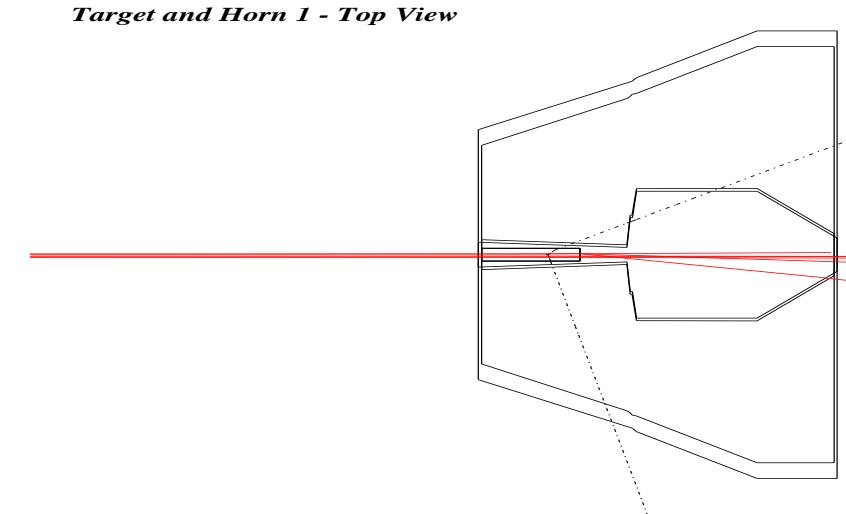
Target is only bathed in a thin envelop of helium (used for cooling).
There is no container around the target in the WBLE design.

Horn simulation in GEANT

NuMI horns/target with 120 GeV p+

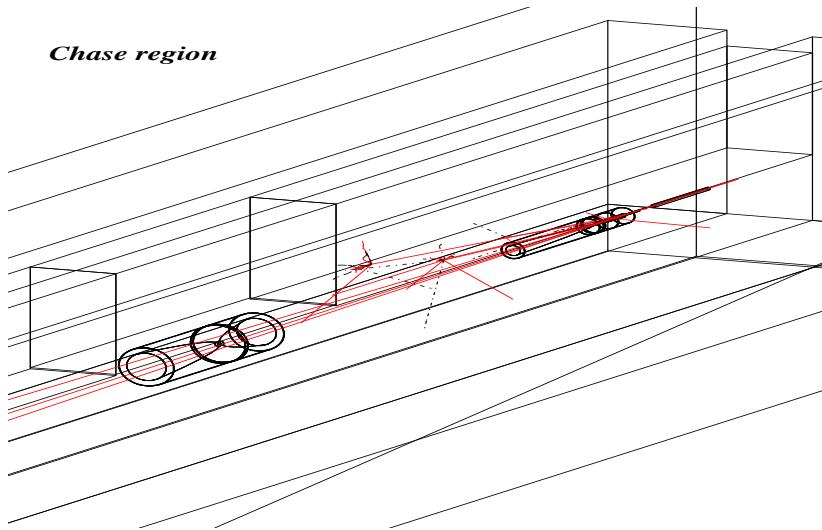


WBLE horns/target with 120 GeV p+

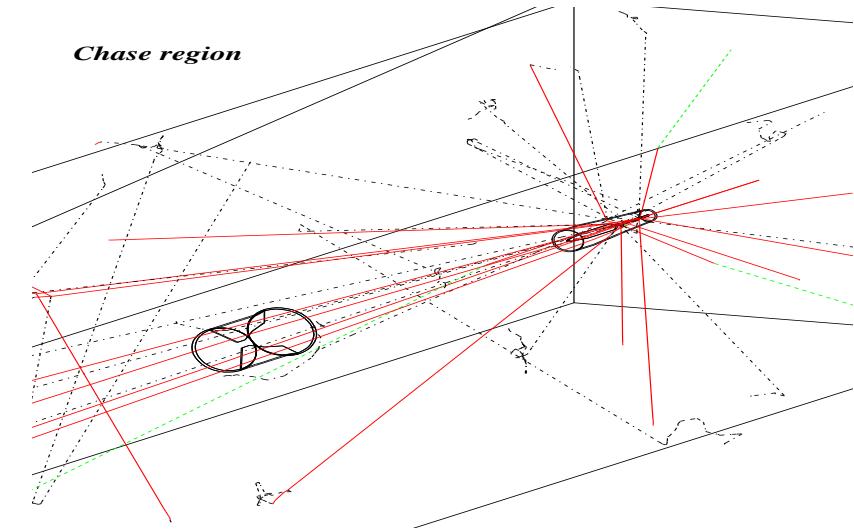


Chase region simulation

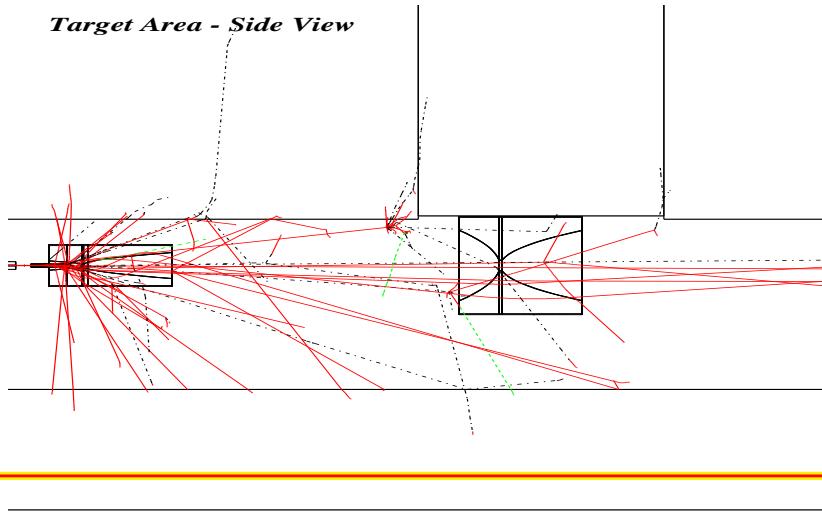
NuMI horns/target with 120 GeV p+



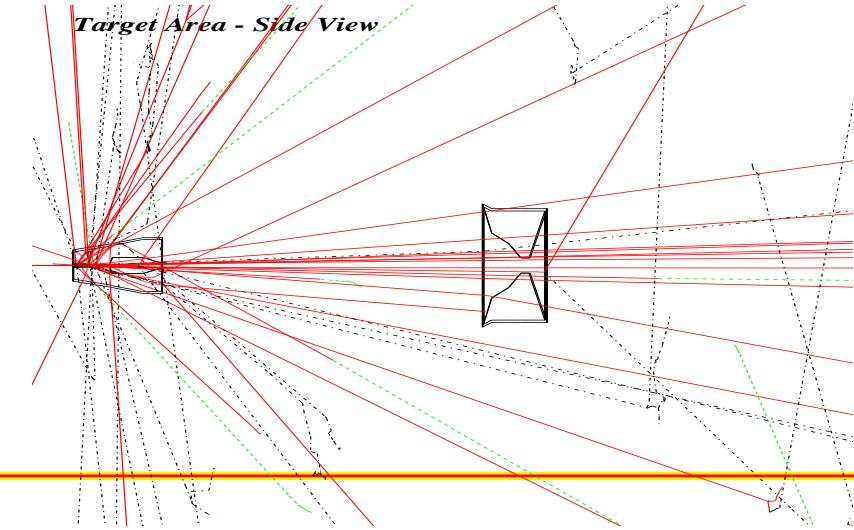
WBLE horns/target with 120 GeV p+



Target Area - Side View



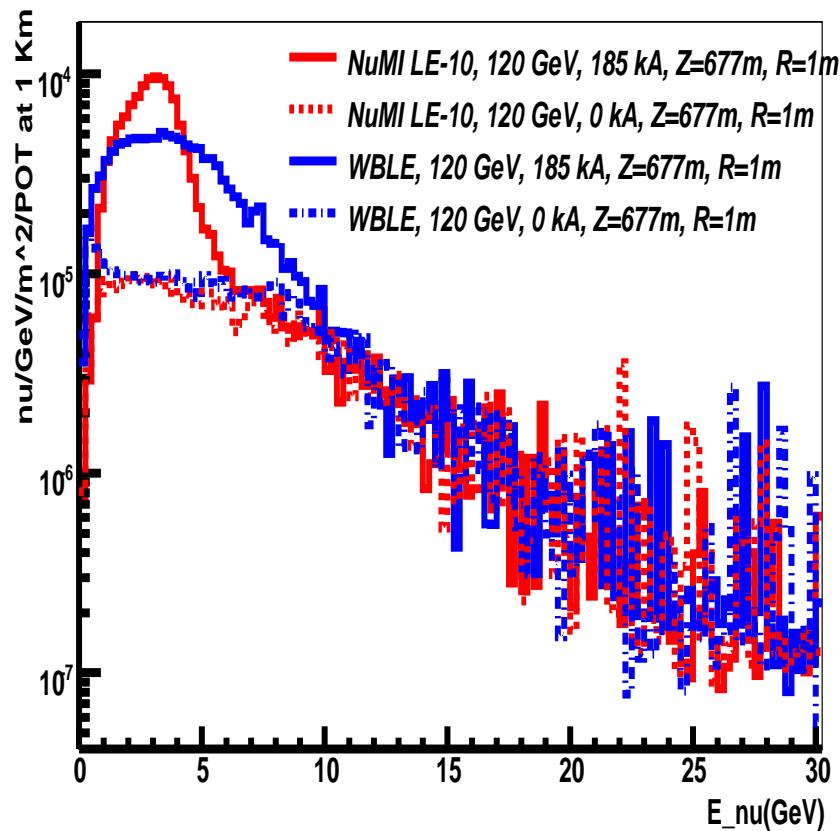
Target Area - Side View



NuMI LE vs WBLE with GNUMI

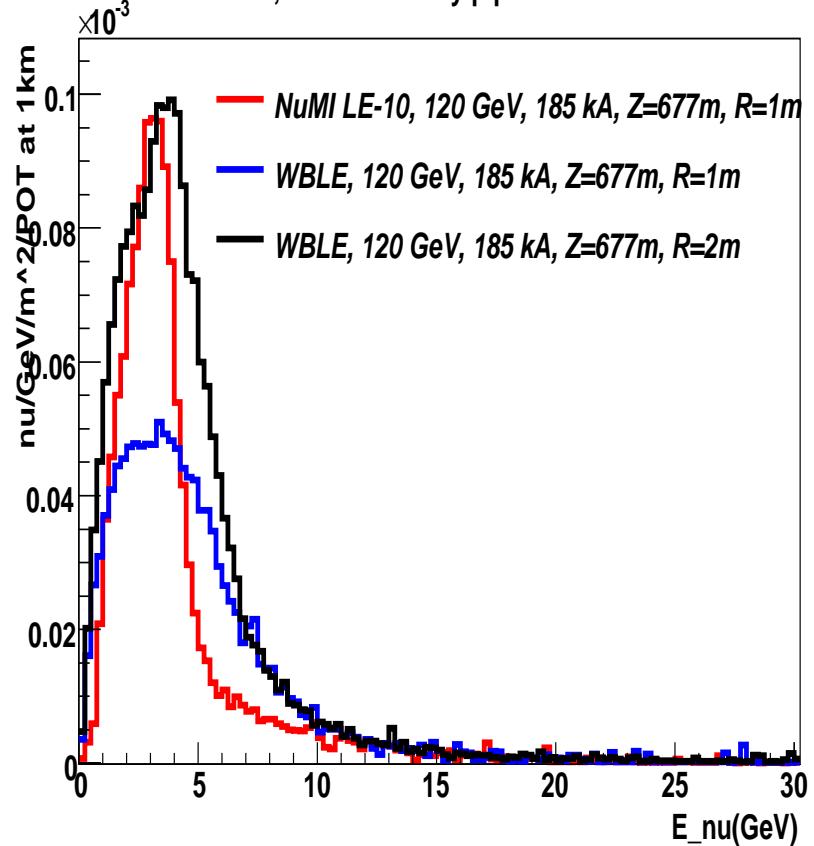
R and *Z* refer to the geometry of the decay volume which is cylindrical.

NuMI LE-10 vs WBLE spectra



1m radius decay pipe

NuMI LE-10 vs WBLE, increase decay pipe radius

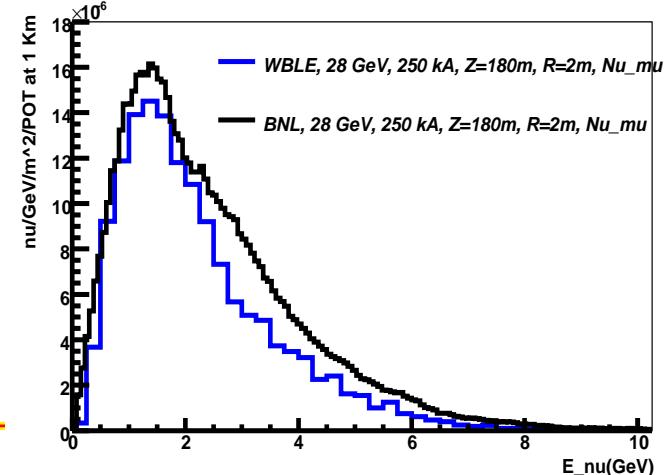
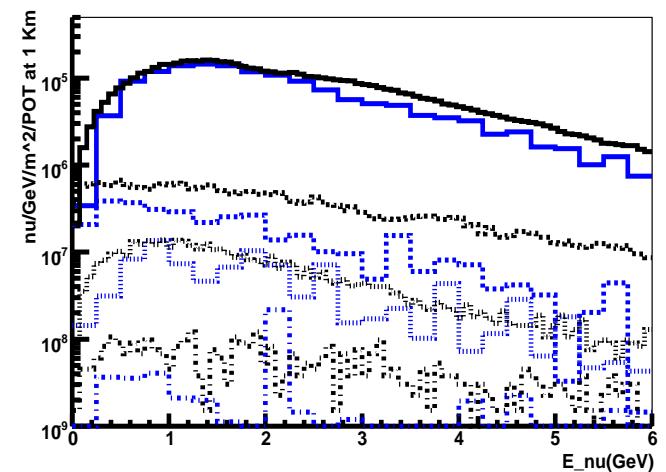
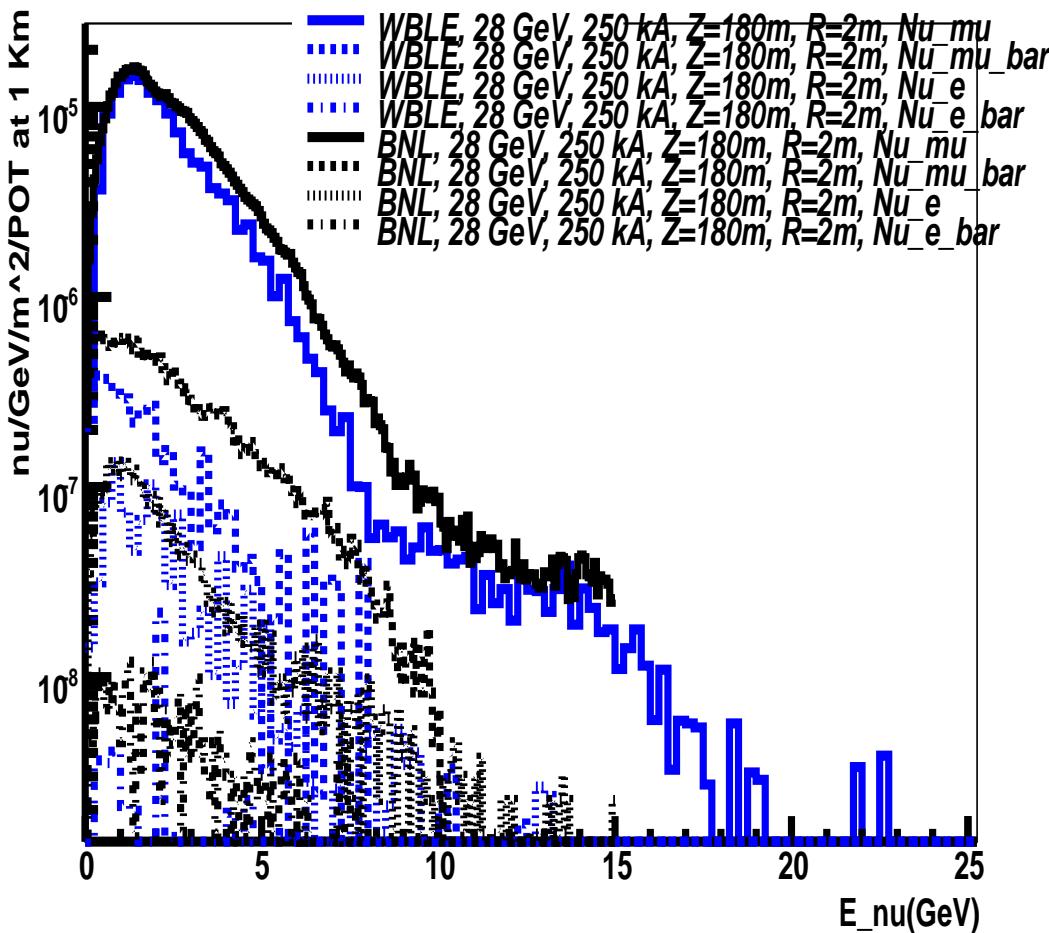


increase to 2m radius

WBLE/BNL-Beam comparison

The current estimates of the physics sensitivities of a wide band on-axis long baseline experiment used a simulation of 28 GeV beam with the same horn design as described previously.

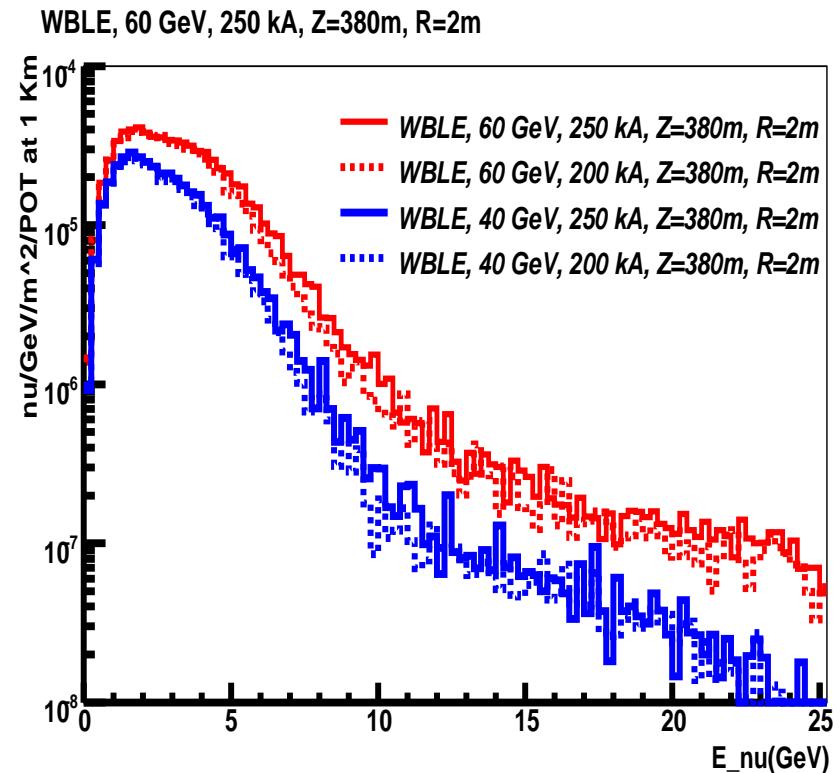
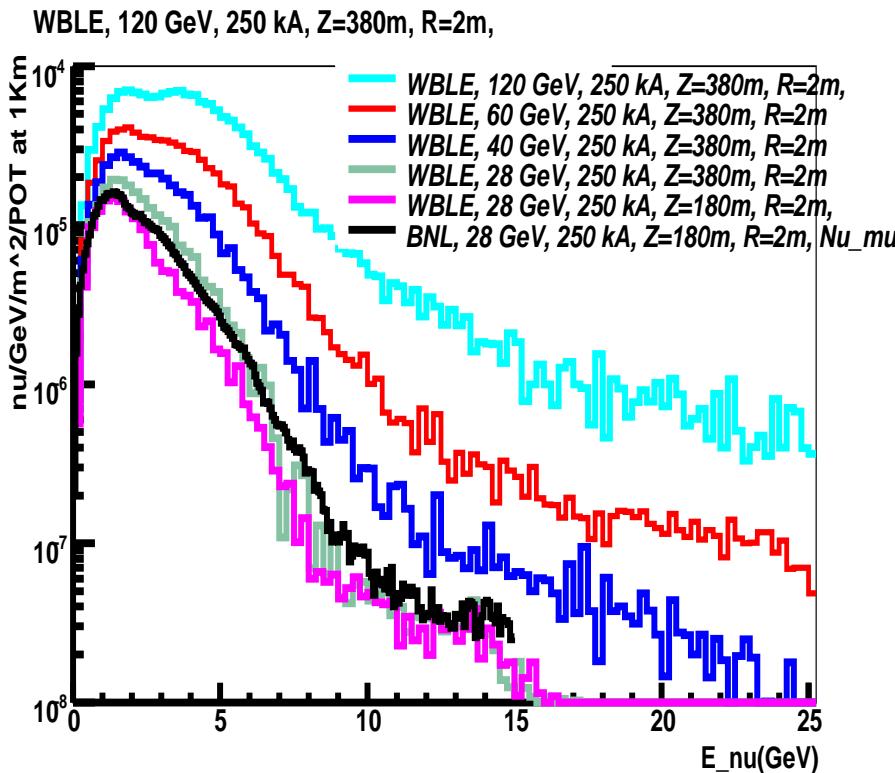
WBLE vs BNL-beam



WBLE Optimization 1

Decay pipe radius chosen to be 2m.

Siting restrictions \Rightarrow decay pipe is ≤ 400 m in length



ν Flux Specifications

| Beam | Peak E | $E, 50\%$ | $E, 10\%$ | Flux | Purity |
|---------------|---------------------------------|----------------|----------------|-------------------------|---------------|
| Scenario | (Flux at 1km) | max flux | max flux | $\frac{\leq 5}{\geq 5}$ | Total |
| | $\nu/(GeV \cdot m^2 \cdot pot)$ | GeV | GeV | | |
| NuMI LE-10 | $3.1 \pm 0.13 \text{ GeV}$ | 4.1 ± 0.13 | 6.1 ± 0.13 | 4.1 | 89% ν_μ |
| Z=677, R=1m | (9.7×10^{-5}) | | | | 1% ν_e |
| WBLE 60 GeV* | 1.6 | 4.4 | 7.1 | 5.0 | 94% ν_μ |
| Z=380, R=2m | (3.9×10^{-5}) | | | | 0.9% ν_e |
| WBLE 40 GeV* | 1.6 | 3.9 | 6.4 | 8.3 | 95% ν_μ |
| Z=380, R=2m | (2.6×10^{-5}) | | | | 0.9% ν_e |
| WBLE 28 GeV** | 1.4 | 3.4 | 5.6 | 15 | 96% ν_μ |
| Z=380, R=2m | (1.9×10^{-5}) | | | | 0.8% ν_e |
| WBLE 28 GeV** | 1.4 | 2.6 | 5.1 | 17 | 97% ν_μ |
| Z=180, R=2m | (1.5×10^{-5}) | | | | 0.6% ν_e |
| BNL 28 GeV** | 1.39 ± 0.04 | 3.11 | 5.81 | 11 | 95% ν_μ |
| Z=180, R=2m | (1.6×10^{-5}) | | | | 0.7% ν_e |

*Horn current = 200 kA. **Horn current = 250 kA

ν_μ CC Interaction Rates - 1

For NuMI (735 km), FNAL-HS (1297 km): 1st osc max is at 1.5 GeV, 2.4 GeV, 2nd osc max is at 0.5 GeV, 0.8 GeV

| Beam | Peak E | CC rate | CC rate | Total CC rate |
|---------------|---------------------------------------|---|---|----------------------|
| Scenario | (CC rate) /(GeV. 10^{20} pot.kT) | 1st osc max /(GeV. 10^{20} pot.kT) | 2nd osc max /(GeV. 10^{20} pot.kT) | /(10^{20} pot.kT) |
| | | | | (distance) |
| NuMI LE-10 | 3.6 GeV | 6.1 | 0.13 | 82 |
| Z=677, R=1m | (18) | | | (735 km) |
| WBLE 60 GeV* | 3.9 | 2.1 | 0.55 | 13 |
| Z=380, R=2m | (2.3) | | | (1297 km) |
| WBLE 40 GeV* | 2.4 | 1.2 | 0.40 | 6 |
| Z=380, R=2m | (1.2) | | | (1297 km) |
| WBLE 28 GeV** | 1.9 | 0.78 | 0.30 | 3.4 |
| Z=380, R=2m | (0.85) | | | (1297 km) |
| WBLE 28 GeV** | 2.1 | 0.56 | 0.30 | 2.4 |
| Z=180, R=2m | (0.67) | | | (1297 km) |
| BNL 28 GeV** | | | | ~ 4 |
| Z=180, R=2m | () | | | (1297 km) |

*Horn current = 200 kA. **Horn current = 250 kA. $kT = kT^{Fe}$

ν_μ CC Interaction Rates - 2

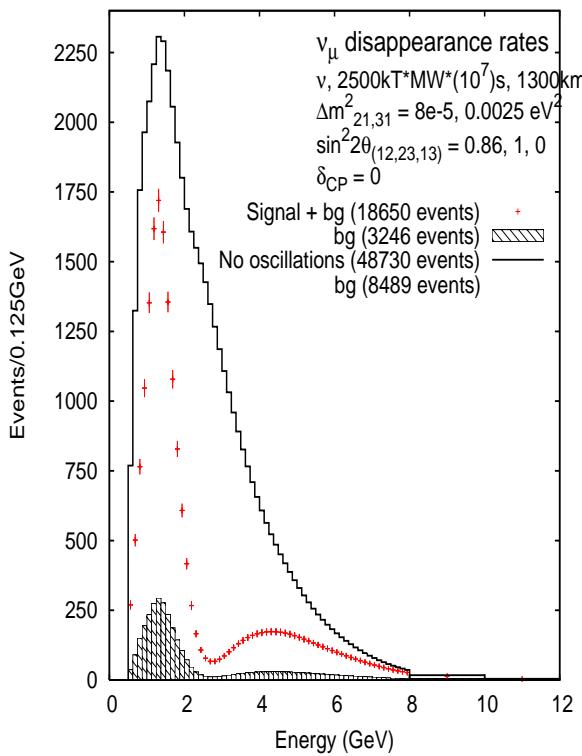
| Beam Scenario | Total CC rate $/(\text{10}^{20} \text{ pot.kT}^{Fe})$ (distance) | Total CC rate $/(\text{MW.kT}^{Fe} \cdot 10^7 \text{ s})$ | Total QE rate $/(\text{MW.kT}^{H_2O} \cdot 10^7 \text{ s})$ |
|---------------|--|--|--|
| NuMI LE-10 | 82 | 427 | 56 |
| Z=677, R=1m | (735 km) | | |
| WBLE 60 GeV** | 15 | 159 | 23 |
| Z=380, R=2m | (1297 km) | | |
| WBLE 40 GeV** | 7.24 | 113 | 20 |
| Z=380, R=2m | (1297 km) | | |
| WBLE 28 GeV** | 3.4 | 76 | 16 |
| Z=380, R=2m | (1297 km) | | |
| WBLE 28 GeV** | 2.4 | 54 | 12 |
| Z=180, R=2m | (1297 km) | | |
| AGS 28 GeV** | ~ 4 | ~ 89 | ~ 16 |
| Z=180, R=2m | (1297 km) | | |

**Horn current = 250 kA

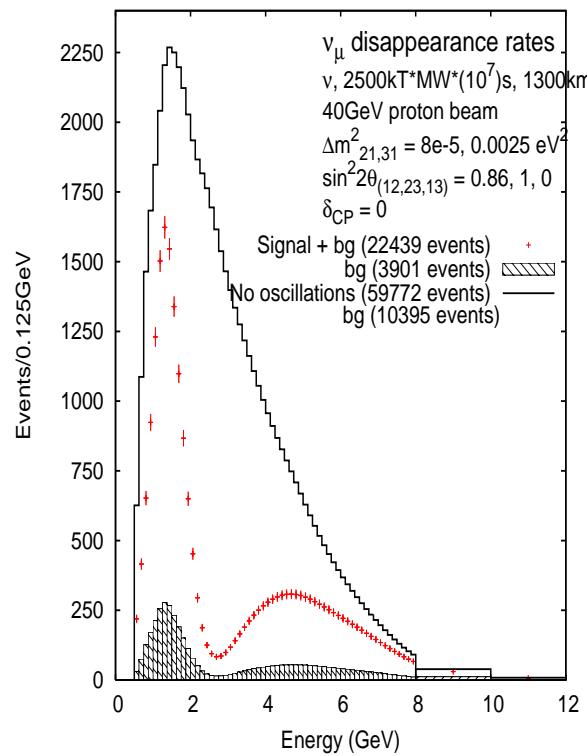
ν_μ Disappearance Spectra (QE)

See Christine Lewis talk.....

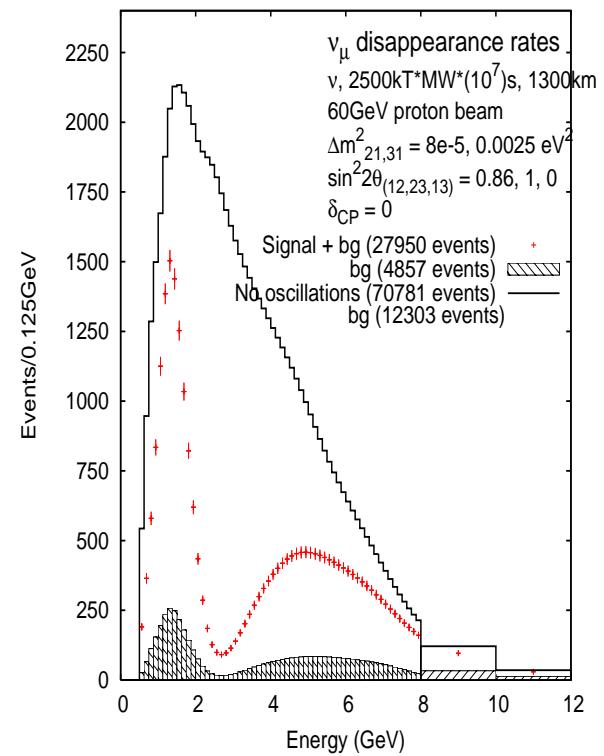
AGS 28 GeV



WBLE 40 GeV



WBLE 60 GeV



Conclusions

- We have completed a preliminary simulation of a Wide-Band Low-Energy on-axis ν -beam from FNAL to DUSEL.
- Preliminary studies have concluded that a 40-60 GeV FNAL-DUSEL beam at 0.5 MW is possible with minor upgrades to the FNAL accelerator complex.
- We find that the ν flux, energy spectrum, and interaction rates from a 40-60 GeV WBLE beam from the MI is compatible with the physics requirements for next generation VLBNO experiments.

To Do:

- Optimization of WBLE target/horn design for higher energy beams
- Obtain a better estimate of decay tunnel allowable geometries based on siting and cost. **Can we make it wider?**.
- Improve optimization critirea for different fluxes
- Use NuMI/MINOS experience to estimate flux uncertainties due to hadroproduction
- Compute oscillation sensitivities for different beams using **GloBES** with best guess on hadroproduction and beam uncertainties (see Christine Lewis' talk).